

PHOTOMETRIC REDSHIFTS: SPECTROSCOPY AT $\Delta\lambda/\lambda \approx 0.1$

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Abstract. I discuss the advantages that photometric redshift techniques offer over traditional (spectroscopic) redshift determination methods. It is shown that the former represents the only means we have of studying the faint distant galaxy population as a whole, and that, in its range of applicability, it delivers excellent results that can add to our knowledge of galaxy formation and evolution processes. Along this line, I also present some of the results extracted from a photometric redshift catalogue of galaxies in the Hubble Deep Field (HDF), including measurements of the star formation density in the high-redshift Universe, morphological evolution of galaxies, and detection of some of the most distant galaxies ever observed.

1. Introduction

To aid our understanding of the processes of galaxy formation and evolution, large databases of distant galaxies are being compiled. The amount of information that can be extracted from them depends on the volume of data available, and the range in lookback time that can be surveyed depends on the depth of the data. Huge advances have occurred in the last few years in both directions.

Multi-object spectroscopy is now performed routinely in observatories all over the world, with instruments such as the 2dF on the AAT that can deliver over 2000 redshifts for galaxies with $B \approx 19.5$ in a single night. The 2dF galaxy redshift survey (Colless, 1999) has already become the largest redshift survey ever, having compiled over 30 000 redshifts. When complete, by year 2000, the final catalogue will hold $\approx 250\,000$ redshifts. Parallel to it will soon run the Sloan Digital Sky Survey (see Loveday *et al.*, 1998), which aims to compile one million redshifts down to magnitude $B \approx 19.0$. In the other direction, the push towards further and further galaxies has also been very successful: colour selection techniques (Steidel, Pettini and Hamilton, 1995) based on the ubiquitous presence of the Lyman limit trough in the spectra of any galaxy and its shift into the optical filters at $z \approx 2.5$, have allowed for the detection of large samples of high-redshift galaxies. The largest sample of galaxies selected in this way (see, for example, Steidel *et al.*, 1998) contains ≈ 700 galaxies in the redshift range $2.5 < z < 3.5$, and ≈ 50 with $3.6 < z < 4.8$.

Another recent step towards the production of larger and deeper redshift surveys has been the development of sensitive and reliable methods to measure redshifts



Astrophysics and Space Science **276**: 965–971, 2001.

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using photometric information. The obvious advantage of these methods is the possibility to apply them to many objects at a time (as many as can be detected in a given field) and down to magnitude levels where spectroscopy would require prohibitive amounts of time – if at all possible. Their main disadvantages are the lack of accuracy (the best results obtained allow at best for $\Delta z \approx 0.10$) and their statistical nature. This is because photometric redshift estimates are based on the shape and broad-band features of the spectral energy distributions (SEDs), like the 4000 Å break, the onset of the Lyman α forest or the presence of a Lyman limit. These features are only identified by means of broad-band photometry, rendering what can be considered an extremely low-resolution spectrum of each object (with ‘resolutions’ in the order of 1000 Å, or $R = \lambda/\Delta\lambda \approx 10$). The HDF observations (Williams *et al.*, 1996) marked the definitive support for these methods. These images, taken by HST in December 1995, represented the deepest view ever obtained of the Universe. The spatial resolution and depth (detection limit $AB(8140) \approx 28.0$), together with the availability of images taken through four different filters (spanning the whole optical range), allowed several groups (see Hogg *et al.*, 1998 and references therein) to present studies based on different photometric techniques. An excellent review on the different techniques is given by Yee (1998).

I will show in Section 2 why photometric techniques are necessary in order to study faint galaxies. In Section 3, I introduce some details of our own method (Fernández-Soto, Lanzetta and Yahil, 1999, hereafter FLY99), as applied to a combination of the HDF images with ground-based IR data. Section 4 is devoted to highlighting the main scientific results that have already been obtained using our catalogue. Section 5 outlines the situation presented by new observations (e.g. the HDF South, Williams *et al.*, 1998) and soon-to-come instruments, and §6 contains a summary.

2. Photometric vs. Spectroscopic Methods at Faint Magnitudes

Photometric techniques are preferred to spectroscopic ones when applied to either very large or very faint samples. In this section I shall use a simple model to show their approximate limits.

Let us first consider a high-throughput multi-object spectrograph (MOS) on a 10 m telescope. We assume it allows for moderate-resolution (5 Å per pixel) spectroscopy of 100 objects per exposure, and disregard the problems usually posed by field crowding. We are also optimistic regarding our redshift determination ability and assume that an S/N ratio of 5 per pixel is enough to secure a redshift in every case. Figure 1a shows the exposure time needed by such an instrument to measure the redshift of a single object of apparent magnitude m . As a comparison, Figure 1A also shows the time necessary to reach a 10σ detection of an object of magnitude m in all four $UBVI$ bands, using the WFPC2 camera on board HST.

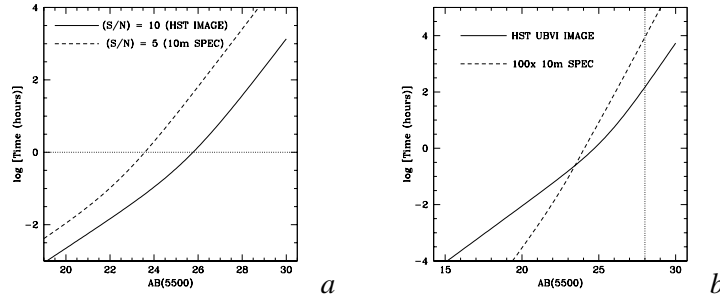


Figure 1. *a)* The continuous line shows the exposure time necessary to reach a 10σ detection of a galaxy in four bands ($UBVI$) as a function of magnitude using the WFPC2 on board HST. The dashed line corresponds to the exposure time needed to obtain an $S/N=5$ spectrum of a source of given magnitude with the instrument described in the text. *b)* Total time necessary to obtain redshifts for *all* sources down to magnitude m in a WFPC2 field using both methods described for panel *a)*.

The experience obtained with the HDF catalogue shows that this is the minimum S/N necessary to obtain an estimate of the source's redshift.

We include now the effect of multiplexing on both techniques: the photometric method allows all objects in the field down to the target magnitude to be analysed simultaneously, while, as mentioned above, the MOS can observe only 100 objects at the same time. Then the galaxy number counts become an important factor, as the number of necessary slits (or fibres) to be allocated grows exponentially with m . This renders the spectroscopic method less convenient by $m \approx 23$, and completely impracticable for $m \gtrsim 25$, as shown in Figure 1*b*.

This simple case shows that, even in the foreseeable future, when spectroscopic facilities are more efficient, photometric techniques will still be necessary in order to obtain information about the faintest galaxies. This is even more so if we add to the equation that the future availability of the *Advanced Camera for Surveys* (ACS), scheduled to be installed on HST during the next servicing mission, will represent a tenfold increase in total efficiency compared to the WFPC2.

3. The Hubble Deep Field North

The HDF-N images, described in Section 1, offer a unique opportunity to apply the photometric techniques. In our first paper (Lanzetta, Yahil and Fernández-Soto, 1996) we presented a method that allowed us to measure redshifts for over 1600 galaxies. A major improvement was added when the IR images of the field became available (Dickinson, 1998). We incorporated those images into our analysis and performed careful photometric measurements (see FLY99 for details) in order to obtain a 'seven-point spectrum' for each object. These 'spectra' were compared to model 'spectra' of different galaxy types at all redshifts between $z = 0$ and $z = 8$, including the effect of the intergalactic medium hydrogen absorption. From

this analysis we obtained a catalogue of *UBVIJHK* photometry and redshift estimates for 1067 objects, complete down to magnitude $AB(8140) = 28.0$. The comparison of our redshift measurements with available spectroscopic redshifts had a first shocking result: in the majority of cases in which the measurements were discordant, the spectroscopic redshifts were shown to be in error (see Lanzetta *et al.*, 1998a). This is very important, as it illustrates the often forgotten fact that redshift determination, no matter which method is used, is a hard task, prone to a multitude of errors.

The final comparison of spectroscopic and photometric redshifts shows that our technique gives essentially perfect results at low redshift ($\Delta z \approx 0.1$ at $z < 1.5$). At high redshift ($z > 2$) we suffer a catastrophic error rate – when high-redshift galaxies are assigned low redshifts by our method – of $\approx 7\%$ (actually comparable to the spectroscopic error rate), with an rms deviation $\Delta z \approx 0.4$.

4. Scientific Highlights

4.1. THE $N - m - z - T$ DISTRIBUTIONS

Figure 2a shows the redshift distribution of the galaxies in our catalogue. The difference between the bright and faint subsample distributions is clear. Observe that the break point used ($AB(8140) = 26$) corresponds to the point where spectroscopic redshift measurement becomes completely impracticable even for 10 m telescopes.

Figure 2b (taken from Driver *et al.*, 1998) shows the $N - m - z$ distribution of galaxies split according to the morphological catalogue by Odewahn *et al.* (1996). The main conclusions obtained from the analysis of these distributions are a high-redshift epoch of formation of elliptical galaxies ($z_f > 3$), and the formation of present-day discs at $z \approx 2$, possibly via hierarchical merging through a stage rich in morphologically irregular galaxies.

4.2. STAR FORMATION IN THE HIGH-REDSHIFT UNIVERSE

One of the questions that has received more attention since the release of the HDF images has been the issue of the star formation (SF) history of the Universe. Pascarelle, Lanzetta and Fernández-Soto (1998) have used FLY99 to show that, contrary to previous results (Madau, Pozzetti and Dickinson, 1998), there is no evidence for a peak in the SF density at $z \approx 2$. The evidence found seems actually to point more in the direction of an essentially flat SF density in the redshift interval $5 > z > 1$, perhaps followed by a decrease to the present value as measured by Lilly *et al.* (1996).

In another study, a search for extremely high redshift galaxies ($z \gtrsim 7$) that may appear in the IR images but not in the optical ones was performed by Lanzetta, Yahil and Fernández-Soto (1998b). The authors found only one candidate in the

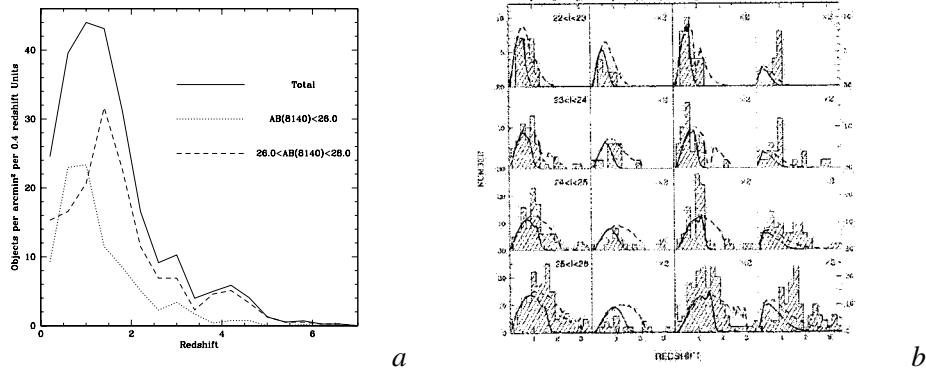


Figure 2. *a*) Redshift distribution of the galaxies in our HDF catalogue. *a*) Morphological redshift distributions for different magnitude intervals (rows) and types (columns from left to right: all, E/S0's, Sbc's, and Sd/Irr's). Overlaid are the zero-evolution (solid-line) and passive-evolution (dashed line) model predictions.

sampled area at the 5σ level of significance, which implies a firm upper limit to the volume density of extremely high redshift unobscured galaxies.

4.3. DETECTION OF HIGH-REDSHIFT GALAXIES

Perhaps the most immediately attractive aspect of the HDF is that it allows us to see further than ever before. An immediate need appears then to identify which galaxies are the most distant. After a selection process, the most promising candidates can be shortlisted spectroscopic observation with large telescopes.

Two of the brightest high-redshift candidates from our catalogue (objects #3, with $z_{\text{phot}} = 5.28$, and #213, with $z_{\text{phot}} = 5.64$) have had their redshifts measured with the Keck Telescope. The spectroscopic measurements show a very remarkable agreement with our estimates: Spinrad *et al.* (1998) measured $z_{\text{spec}} = 5.34$ for object #3, while Weymann *et al.* (1998) obtained $z_{\text{spec}} = 5.60$ for object #213. Object #3 is very interesting: it is formed by two separate clumps (see Figure 3, taken from Spinrad *et al.*, 1998).

5. The Future: Looking South with Different Eyes

A second HDF was observed in October 1998 in the southern sky. The new STIS and NICMOS cameras on board HST were used in parallel with the WFPC2, producing three extremely deep fields (Williams *et al.*, 1998). All fields were also observed by the ESO VLT and NTT telescopes in Chile and the AAT telescope in Australia.

This second HST *coup de force* represents much more than just a second copy of the same science: the infrared images taken with the NICMOS camera are by

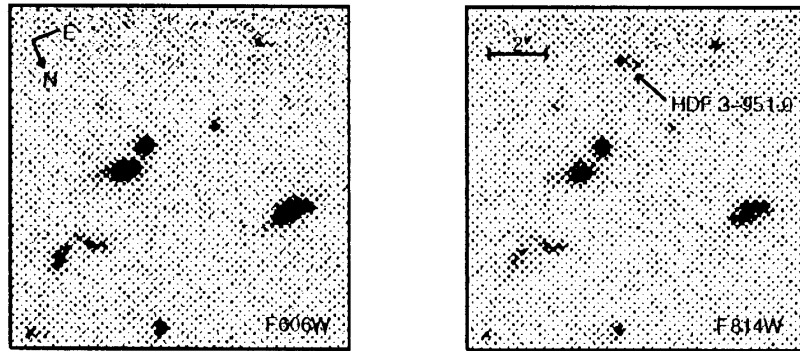


Figure 3. The panels show the *F606W* and *F814W* images of object #3 (HDF 3-951.0 in the Williams *et al.*, 1996, catalogue). The effect of the redshifted Lyman α absorption is clearly perceived in the blanketing of the bluer image.

far the deepest images available, and they will potentially allow for the detection of galaxies with redshifts up to $z \approx 15$. The ground-based images that complement the HST ones are also much higher quality than any obtained for the HDF-N, which allows for much better photometry and subsequently much more precise redshift estimation. Our group has already completed the redshift measurement of the objects in the HDF-S NICMOS and WFPC2 fields, and we are now in the process of refining and analysing the results. The catalogues can be obtained from <http://www.ess.sunysb.edu/astro/hdfs/home.html>.

The next steps will be taken in two different directions. From a practical point of view, the deployment of the ACS as a new instrument on board HST will mark a breakthrough for all morphological galaxy surveys. The efficiency and area of its detectors will allow the equivalent of one HDF to be taken each day. Undoubtedly many of the projects undertaken will include the collection of deep, high-resolution, multicolour images, ideal for studying via photometric redshift techniques. On the other hand, a worrisome aspect of the technique is the uncertainty in the redshift range $1.5 < z < 2.5$. This is a key epoch for galaxy formation and, due to the lack of spectral features, we have no way of securing the identification of galaxies in that redshift range. Our technique should be able to single them out, but caution must be exercised until a sample of spectroscopically confirmed objects is available for comparison. This will have to wait until the new generation of near-IR spectrographs is up and running.

6. Summary

I have shown that photometric redshift techniques are useful in cosmology. They can be applied in those cases in which the objects are too numerous or too faint to be observed spectroscopically, whenever some accuracy can be sacrificed for

the sake of the increase in numbers. Moreover, they are the only means we shall have in the foreseeable future of extracting all the information produced by the ever-increasing amount of large facilities and survey instruments available.

As an example, I have presented the analysis performed by our group on the HDF-N images, together with the most interesting results derived from our redshift catalogue. These results include the morphologically segregated redshift-magnitude distribution of a large sample of galaxies, the study of the star formation density in the high-redshift Universe, the search for very high redshift galaxies at $z \gtrsim 7$ and the discovery of some of the most distant galaxies ever observed.

Acknowledgements

I would like to thank all of my collaborators in this project, particularly Ken Lanzetta. I would also like to thank Simon Driver and Hyron Spinrad for allowing me to use figures from their papers, and the whole HDF team for having put together such an interesting set of photons.

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